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Oct.26, 2000 Nov.28, 2000 document OHS: OH-airglow Suppressor for the Subaru Telescope Fumihide Iwamuro,[1] Kentaro Motohara,[2] Toshinori Maihara,[3] Ryuji Hata,[1] and Takashi Harashima,[1] [12pt] [1] *Department of Physics, Kyoto University, Kitashirakawa, Kyoto 606-8502 E-mail(FI): iwamuro@cr.scphys.kyoto-u.ac.jp* [2]*Subaru Telescope, National Astronomical Observatory, 650 North Aohoku Place, Hilo, HI 96720, USA* [3]*Department of Astronomy, Kyoto University, Kitashirakawa, Kyoto 606-8502* This paper describes an OH-airglow Suppressor (OHS) for the infrared Nasmyth focus of the Subaru telescope. OHS has the capability of eliminating 224 airglow-lines in the J- and H-bands, which are major sources of background radiation at near-infrared wavelengths up to 2 μm. Specifically, it is a pre-optics system installed between the telescope and an infrared camera/spectrograph (CISCO). The suppressor reduces sky background emissions to 1/25 and its throughput is 40%. As a result, the S/N gain achieved with OHS is more than 1mag compared to the typical spectroscopic approach. The limiting magnitude measured during a test observing run was found to be H=21.1mag ($\lambda/\Delta\lambda$=210, S/N=5) in the standard 4000sec exposure sequence.

cosmology: instrumentation: spectrographs — infrared: general

headings

Introduction Rapid progress has continued to be made in the study of the high-redshift universe over the last decade by the development of telescopes, large-format arrays, and observation techniques. To date, a considerable number of high-z galaxies have been spectroscopically identified, and the nature of these galaxies has been investigated, mainly using their broad-band colors. However, it is impossible to separate the effects of age and extinction only from these colors. This problem has prevented the exact features of high-z objects from being obtained. More detailed information — rest-frame optical spectra — is required for the further study of these objects.

It is extremely difficult to obtain the rest-frame optical spectra of distant galaxies, but several groups have succeeded in detecting some emission-lines of high-z radio galaxies (Eales, Rawlings 1993, 1996; Evans 1998) and of Ly break galaxies (Pettini et al. 1998) in the near infrared J- to K-bands. Two antithetical concepts can be seen in their results. One is a lower spectral resolution to detect a faint continuum and to achieve wider wavelength coverage, and the other is a higher spectral resolution to avoid the effects of strong airglow-lines. OHS is an instrument that can merge these two concepts, achieving a high sensitivity for a faint continuum and a wide spectral coverage.

Before designing OHS for the Subaru telescope, we worked forwards confirming the basic performance of the suppressor by using a proto-type instrument (Iwamuro et al. 1994) from 1992 to 1995 in the University of Hawaii's 2.2m telescope on Mauna Kea. The total design of OHS described here is based on our experience from these test observations. After that, we developed an infrared camera/spectrograph (CISCO: Motohara et al. 1998) as the back-end instrument of OHS, and OHS itself was mounted on the Nasmyth stage of the Subaru telescope at the end of 1999.

The optical design and mechanical design of OHS are described in sections 2 and 3, the details of the airglow mask are reported in section 4, and the performance of the OHS/CISCO system during its first nine months of operation is summarized in section 5.

Optical Design Figure 1 shows the optical layout of OHS. The focal ratio of the infrared Nasmyth focus of the Subaru telescope is $f/13.2$ with the image rotator. As the figure shows, incident rays coming through the entrance slit in the gap of the two gratings are reflected by the collimator mirror, upper grating, camera mirror, mask mirror, camera mirror again, lower grating, refocus mirror, and pick-off mirror. Here, the incident beam including the sky background and the object flux is dispersed by the upper grating and focused onto the mask mirror, where a bar-code-like mask is installed. This mask absorbs almost all airglow-lines; the remaining parts are reflected and re-combined by the lower grating. The upper layer (from the entrance slit to the mask mirror) and the lower layer (from the mask mirror to the pick-off mirror) must be separated to pick out the refocused slit image from the optical path between the refocus mirror and the entrance slit without attenuation.

This configuration also reduces the contribution of scattered light from bright incident beam before airglow rejection to the final image. Any optical aberration caused by the spherical camera mirror is reduced by the collimator mirror and the refocus mirror with their hyperbolic surfaces. However, the separation between the upper and lower layers is still restricted, i.e., the size of the entrance slit is 15mm (28$''$) long by 0.5mm ($0.-2pt''93$) or 0.25mm ($0.-2pt''47$) wide (see section 3).

The upper and lower gratings have exactly the same optical parameters: 245 lines mm^{-1} and a blaze angle of 37°. These gratings disperse and then re-combine J-band (1.11–1.35μm) and H-band (1.48–1.80μm) light with the order of fourth and third, respectively. The dispersed J- and H-band light is focused onto the mask mirror simultaneously by the large spherical camera mirror 1.3m in diameter. The spectral resolution on the mask mirror is $\lambda/\Delta\lambda$=5500 for a $0.-2pt''93$ slit (and double for a narrower slit), while the rejection resolution is 3900, because the element of the mask is 1.4 times wider than the slit image (see section 4). Figure 2 shows spot diagrams at the end of the OHS optics and on the mask mirror. Since the slit length is quite small compared with the focal length of the collimator, the spot size is almost fixed inside the slit. The aspheric corrector plates placed in front of the gratings can reduce the spot size noticeably, but they can also cause a lower throughput and ghost airglow images on the mask mirror, posing a serious problem for the OHS concept. The squares in the spot diagrams correspond to the pixel scale of CISCO ($0.-2pt''105$); the optical aberration in CISCO (Motohara et al. 1998) is slightly larger than these squares. Accordingly, the optical aberration in OHS does not have a large effect on the final image.

Mechanical Design All of the optical elements of OHS are equipped in the upper frame supported by three hydraulic jacks on the base frame, which allows the direction of the instrument to be adjusted (Figure 3). The base frame is also slidable to the waiting position by hand despite a total weight of 3,000 kg and a size of 5m×3m. The entrance slit, the gratings, and the pickoff mirror supports are mounted on the retractable stage, which is drawn back at the waiting position to avoid collision with the structure of the telescope. The entrance slit has five positions: pinhole, narrower ($0.-2pt''47 \times 28''$) slit, wider ($0.-2pt''93 \times 28''$) slit, open ($20''\times28''$), and close. The collimator/refocus mirror support and mask mirror support are mounted on the adjustable stages driven by stepper motors along the optical axis. The dispersion power on the mask mirror can be tuned to the scale of the airglow mask by adjusting the position of the mask mirror along the optical axis, because the separation between dispersed beams changes as the position is moved (see Figure 1). The airglow mask focus is adjusted by moving the position of the collimator mirror. Since these adjustments can be done only for real airglow-lines, the positions of these elements are controlled from the observation room.

CISCO is supported by an adjustable stage featuring three electric jacks and three sliding or rotating stages (Figure 4). CISCO is also used as a general infrared camera with a field of view of $1.-2pt'8$ square attached to the Nasmyth focus directly with this adjustable stage (after OHS is moved to the waiting position). We can adjust the direction of the optical axis and the position of the camera whichever the camera is placed.

Airglow Mask The airglow mask is made of a thin stainless steel plate 0.2mm thick, and processed by photochemical etching (Figure 5). The surface of the mask is coated with special black paint, which absorbs more than 99.9% of all near-infrared light up to 2μm. A total of 224 OH and O_2 airglow-lines in the J- and H-bands are rejected here, while the effective opening area is 74.4%. The width of the element of the mask is 0.7mm, which is a factor 1.4 times the width of the slit image of 0.5mm (this is because there may be small differences between real airglow-lines and the position of the mask element). The mask has overlapping patterns of airglow-lines in the J- and H-bands with different orders of the grating. Although this configuration is not favorable considering the instrumental throughput, we can obtain airglow-suppressed spectra in both bands simultaneously. From this point of view, we do not reject all broad molecular oxygen lines near 1.28μm; this rejection requires a very wide mask for complete removal.

The wavelength of the OH-airglow emission-lines was calculated from the transition levels of the OH radical reported by Coxon (1980), and Coxon, Foster (1982). The judgment of whether to reject the lines or not was made by referring to the airglow spectra observed in Maihara et al. (1993). The airglow-lines rejected by this airglow mask are listed in Table 1.

Test Observations and Verified Performance Following the installation of OHS at the end of 1999, test observation runs were carried out about every two months. In this section, we first summarize the results of these observations, and we then describe the performance of this system verified by several spectra of faint objects.

The typical observation procedure starts from what we call the "imaging mode", in which the slit of OHS is opened and CISCO is operated as an infrared camera (Figure 6). The airglow-suppressed area corresponds to the black stripe at the center of the sky image called the "dark lane", where the airglow-lines are in phase with the airglow mask. The effective area of the dark lane is $1.-2pt''3 \times 28''$. After an object is guided into this area, about a dozen frames are taken by nodding the telescope along the dark lane between the exposure sequences. These frames are used not only for photometry but also for confirmation of the object location in the dark lane at each nodding position. Next, the observation mode is switched to what is called the "spectroscopic mode", in which the slit of OHS is moved to the center of the dark lane, and in CISCO, the width of the variable slit is reduced and the JH-band grism is selected. The standard exposure time of 1000sec reaches the background limited condition with multiple-readouts of six times the detector. At least four times of the exposure should be done to avoid bad pixels and unexpected hot pixels; accordingly, the standard exposure time comes to be more than 4000sec.

The total system efficiency was measured through observations of the UKIRT faint-standard stars in the imaging mode. The efficiency was 8.3% in the J-band and 12.2% in the H-band. The throughput of the OHS part was estimated to be 40% in both bands by comparison of the throughput with and without OHS.

The spectroscopic images taken by OHS are compared with images taken by the direct spectroscopy of CISCO in Figure 7. The observable spectral range for the CISCO JH-band spectroscopy is from 1.044μm to 1.816μm limited by the order sorting filter paired with the grism, while the range becomes discontinuous with OHS, because the light out of either end of the mask mirror does not reach the detector. Almost all airglow-lines except broad O_2 lines in the J-band are rejected by OHS; this is also shown in Figure 8. The rejection factor of the airglow-lines is 25.

The gain of OHS is illustrated in the lower half of Figure 7. The object is radio galaxy 4C +40.36 (z=2.269) as observed by CISCO (May 24) and by CISCO with OHS (May 23). It is quite obvious that OHS has a large advantage in terms of sensitivity for faint objects even with a shorter exposure time. Since the object and background flux are in proportion to η and η/f_s, respectively (η: throughput, f_s: suppression factor), the gain of OHS is estimated simply by the following equation.

equation Gain $= \eta\sqrt{\eta f_s} = \sqrt{\eta f_s}$